Supernova Explosions

Summary:

Students are reminded that the universe is made up of elements and that the heavier elements are created inside of a star. They are introduced to the life cycle of a star and how the mass of the star affects the process of fusion and the outcome of the star. The physical concept of balancing forces is discussed and an experiment is conducted to show what can happen to a soda can when the interior and exterior forces are not in equilibrium. An analogy is made between this experiment and core collapse in stars. Finally, it is demonstrated how mass can be ejected from a collapsed star. This is how the heavier elements are dispersed throughout the universe in a supernova explosion.

Purpose:

To understand the life cycle of a star and the origin of the heavy elements in the universe.

Audience:

~ 20 students (grade range 6^{th}-9^{th}) in a group works well

Objectives:

1. Introduce the life cycle of a star
2. Discuss the forces at work inside a star
3. Understand the role of mass in determining the extent of fusion and the fate of a star
4. Learn about core collapse of a star
5. Simulate mass ejection and understand how to populate the universe with the heavy elements from the interior of stars during a supernova explosion

Materials:

- colored balloons (1 of each of the following colors: red, orange, yellow, green, blue, and violet)
- empty aluminum soda can
- hot plate (or Bunsen burner and screen/ring setup)
- large bowl of cold water
- tongs or oven mitts
- Hoberman sphere
- basketball (or soccer ball)
- tennis ball

Activity Procedure and Discussion:

This activity can be completed in 45 minutes. A sample script and flow of discussion follows.

Part I: Review concept of elements (~ 10 minutes)

As the activity begins, ask the students what they have learned about elements in the universe (if they have already participated in the Elements and You activity) or what they know about elements (if they have not participated in the Elements and You activity). Remind them that the elements of which they are made (carbon and oxygen, for instance) are very rare in the Universe and are made in stars. They should know that the stuff created inside stars needs to get out somehow (in a big explosion). Try to ask them questions and unearth any possible misconceptions before the rest of the activity begins. What is an element? What are different kinds of elements? What is an atom? What is an atom made of? (Possibly a misconception will be the distinction between an atom being the smallest unit of an element, but not the smallest unit of matter. Atoms are made of protons, and neutrons, and have electrons orbiting around them.)

In this activity, and with your help, we are going to figure out how to make a star EXPLODE in order to distribute different elements into the universe! Unfortunately, not all stars will become supernova, so first we need to understand the life cycle of stars...

Part II: Stellar Life Cycle (~ 10 minutes)

How do different sized stars behave and how do they age?

A key concept to reinforce is that there are three different types of pressure at work in a star – pressure from gravity, pressure from hot material, and pressure from “dense" (degenerate nuclear) matter. Most important is that the self-gravity of a star is trying to push everything down, and stars use the other two types to fight it.

1. All stars start fight gravity by releasing large amounts of energy through fusion. Fusion is the process whereby different types of elements are created. The more mass that a star has, the hotter it can get in its core, and the more it can use energy from fusion to support itself from collapse.
2. Ultimately, all stars will loose the ability to fuse elements. At this point, the core may be dense enough to support itself like a chair supports you when you sit on it. This depends on how massive the star is. (The more stuff you pile onto a chair, the more likely it is to break!) The following description (adapted from http://www.adlerplanetarium.org/) demonstrates at what stage a star looses this ability to fuse elements and whether the star is light enough to support itself by other means.

Note to Astronomers: We use table B1 from Gray to roughly convert balloon color to size.

Spectral Class	**Relative Mass**	**Balloon Color**	**Rel Radius**	**Comments:**
m2	0.4	Red	0.6	Fuse H ◊ He -- stable
k0	0.8	Orange	0.8	
g4	1	Yellow	1	Fuse H◊ He, C, O – stable “white dwarf”
f0	1.6	Green	1.5	
b3	8	Blue	4.3	Fuse H ◊ He ◊ Fe – run out of fuel
o8	23	Violet	7.4	Supernova upon loss of support

Red/Orange Stars: Have two students blow up a red and an orange balloon. These are very cool stars. They can fuse hydrogen into helium, but not much else. The helium in the core won't get hot enough to fuse together. The star will cool off and become fairly useless. The same kind of pressure that lets chairs and tables stop things from falling due to gravity will hold up the star against gravity until the end of time.

Yellow/Green Stars: Have two more students blow up a yellow and a green balloon. These stars are similar to our Sun. They can fuse hydrogen into helium. It can also get hot enough to fuse the helium in carbon and oxygen. But that's all. The star can't get hot enough to fuse carbon or oxygen, but the star is light enough that the dense carbon/oxygen core can support the star. This is called a white dwarf. No supernova here.

Blue/Violet Stars: Two more students blow up a blue and violet balloon. Now we are getting somewhere! This is a really hot and really massive star, and it can do all the things the other stars can do and more! Fusion of elements will continue until the core is iron. But here, we run into two problems: (1) iron can't fuse into anything else (they may have learned this in the Elements and You activity), and (2) the star is too massive to be supported by the iron core in the same way the other stars are. So we've reached a breaking point. The iron core is going to get hotter and hotter and hotter until the electrons and protons in each iron atom combine to form neutrons. At this point, we have a sudden loss of support, and a lot of vacant space (since neutrons are much smaller than atoms.)

Part II: Implosion (~ 10 minutes)

Why do Stars Collapse?

The core of the blue/violet star now has no way supporting itself against gravity. So what happens when there is a sudden decrease in pressure that supports the core?

Demonstration of core collapse (adapted from http://chandra.harvard.edu/graphics/edu/formal/demos/contraction.pdf)

> Place approximately two tablespoons of water in an empty aluminum soda can. Set the can on a hot plate or a screen/ring setup over a Bunsen burner. Heat the can until the water starts to boil. When the steam starts to come out of the opening in the top of the can, quickly pick up the can with an oven mitt or tongs and invert into a bowl of cold water. The can will instantly implode with a crunching sound.

Related Physics: The empty aluminum can is held in equilibrium by the pressure of the air inside the can directed outwards and the pressure of the air outside of the can directed inwards. Heating the water in the can causes the water to turn into steam. The steam drives all of the air out of the can. Now the can is held in equilibrium by the pressure of the steam pushing outwards (analogous to the radiation pressure in the core of the star) and the pressure of the air outside of the can directed inwards (analogous to the gravity of the star directed inwards). When the can is inverted over the cold water, the steam instantly condenses. (This is similar to the sudden "condensation" of electron degenerate matter to neutron degenerate matter.) Now there is no pressure inside the can. The outside air pressure then causes the can to implode (analogous to the core of a star collapsing without radiation pressure as a counterbalance to gravity.)

So we saw that the can imploded because the pressure inside the can disappeared. So why do we get an explosion? Here we have a cool plastic sphere (show them the Hoberman sphere), and we can use it to simulate the imploding core of a star. (Open the sphere all the way, and then let it collapse under its own gravity.) So what happened after the sphere collapsed? That is right, it "bounced" at the end. It started to collapse, but then the collapse stopped because stuff falling in from one side collided with the stuff falling in from the opposite side.

Part III: Mass Ejection (~ 10 minutes)

How does the materials from the interior of a star find if way out?

Now the core of star collapsed, and then bounced when it collided with itself. But a star is made up of more than merely a core, it also has an atmosphere like the Earth, only much thicker. So when the core collapses, what happens to the atmosphere?

Demonstration of Atmosphere ejection (adapted from http://chandra.harvard.edu/graphics/edu/formal/demos/ejection.pdf)

First drop the tennis ball and basketball individually on the floor so that the students can see how far above the floor the basketball and the tennis ball rebound. Then place the tennis ball on top of the basketball and hold them out in front of you. Let go of both balls at the same time so that they fall towards the floor together. When the two balls hit the floor the tennis ball will suddenly rebound with enough energy to hit the ceiling.

Related Physics: When the core of the star implodes it contracts catastrophically, just like the imploding can. At the end of the contraction the material in the core comes together with such a large amount of force that it rebounds. As the core (represented by the basketball) contracts, all the outer atmospheric layers (represented by the tennis ball) are also contracting and following the core. They are less dense and take a little longer to contract than the core. When the core (basketball) rebounds, the atmospheric layers (tennis ball) are still in-falling towards the core. The rebounding core meets the incoming atmospheric layers with enough energy to literally blow the atmospheric layers away from the star due to the transfer of momentum from the basketball to the tennis ball. This is the supernova explosion.

Part IV: Wrap-up (~ 5 minutes)

- Not all stars will end their lives in a spectacular supernovae. Without help, only the ones that are massive enough to try and fuse iron will do so.
- Every star is fighting against gravity, and they start doing this using the energy released by fusing hydrogen into helium. Some stars will only get this far, and those will end up fighting gravity the same way chairs and table fight gravity. Other stars can get hot enough to fuse helium, etc.
- The hottest/most massive stars will get to the point where they have a degenerate iron core, but this is a problem because iron doesn't fuse and stars are too massive to be supported the other way.
- There is a sudden drop in the core pressure of a massive star, the whole thing will start to implode. Stuff in the core and bottom of the atmosphere

will "bounce" when it meets other stuff falling in from the other side, and this bounce will cause the outer layers of the atmosphere to violently explode. In the remaining core, the neutrons might be able to hold up what's left. This is what's called a neutron star, and it can be observed in the X-rays. If the remainder of the core is too massive even for neutrons, it will become a black hole.

- Most stars have companion stars. Sometimes yellow stars can become supernovae if they have a companion which helps them by adding more mass – the same way you can collapse a table pile up enough stuff on it.